Pre-Print

Optical Engineering. Accepted for publication June 2003

Progress in Development of Multiple Quantum Well Retromodulators for Free-Space Data Links

G. Charmaine Gilbreath,[1] W. S. Rabinovich, Timothy J. Meehan, Michael J. Vilcheck, Mena Stell,[2] Rita Mahon,[3] Peter G. Goetz, Eun Oh, John Vasquez, Kerry Cochrell,[4] Robert Lucke, and Sharon Mozersky

U. S. Naval Research Laboratory

Washington DC 20375

http://mrr.nrl.navy.mil

[1] Member, Gilbreath@rsd.nrl.navy.mil
[2] Author is with Research Support Instruments, Inc., Lanham, MD 20706
[3] Author is with Jaycor, Inc., McLean, VA 22102
[4] Author is with ITT Industries, System Division, Alexandria, VA.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Progress in Development of Multiple Quantum Well Retromodulators for Free-Space Data Links**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue, SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**28**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Abstract

This paper is an update in the progress of the development of NRL's Multiple Quantum Well retromodulators for compact, low power communications. We report results for data-in-flight on a small, unmanned aerial vehicle at up to 5 Mbps, in preparation for real-time video transfer using an array of devices. This data was taken at Chesapeake Bay Detachment. We also report transference of color video using wavelet compression at 15 and 30 frames per second, at 4 to 6 Mbps in lab, at eye safe intensity levels. The unit is a cornercube modulator using a 980 nm shutter. A five-element array was used for the data-in-flight. First results of our 1550 nm devices are also presented as is progress in a "Cats Eye Retromodulator".

Key Words: MQW Retromodulators, Modulating Retroreflector(s), Retromodulators; Cat's Eye Retromodulator; Free-Space Optical Communications

1.0 Introduction

Due to its promise of wide bandwidth, freedom from frequency allocations issues, comparatively small communications terminals, and low power requirements, free space optical communications has emerged in recent years as an attractive alternative to the conventional

Radio Frequency (RF) approach. There are many applications, where reducing the parasitic payload requirements for the onboard communications system would be advantageous and the Naval Research Laboratory (NRL) has been developing multiple quantum well (MQW) retroreflectors for just this purpose.[1,2]

In this paper, we report progress in the implementation of the wide aperture MQW modulating retroreflector (MRR) for video and multiple Mega-bit-per-second (Mbps) data transfer for compact, lightweight, low power optical data transfer.

The device couples an electro-absorptive narrow band tunable shutter with a standard optical corner cube. It is lightweight (on the order of ounces), low power (milliwatts), compact (centimeter-level diameters), and radiation-hard.[3] When coupled with a sensor and drive electronics, the package can serve as the communications payload for a remotely located platform.

The payload is interrogated by a laser and modulated by the shutter. The modulated retroreflected light is received and demodulated at the transmit/receive location. This technique is especially suited to asymmetric links where the communications payload located remotely can be quite small - the size of a quarter for a single device and the size of a fist for an array. This asymmetry is enabled by the range-to-the-fourth loss inherent in the use of retroreflected links. That is, the received power in the far field is proportional to:

$$\frac{P_{laser} \cdot D_{retro}{}^{4} \cdot D_{rec}{}^{2} \cdot T_{cl}^{2} \cdot T_{atm}{}^{2}}{\theta_{div}{}^{2} \cdot R^{4}} \qquad (1)$$

where P_{laser} is the transmit power, D_{retro} is the diameter of the retroreflector, D_{rec} is the receiver diameter, T_{atm} is the transmission coefficient of the atmosphere, T_{cl} is the transmission coefficient of clouds, θ_{div} is the divergence of the transmit beam, and R is the range. The onus

of the link consequently falls on the power of the transmitter, the size of the receive telescope and the quality of the detector and receiver. Although the range-to-the-fourth component clearly dominates loss of signal in air, off-the-shelf components can support multi-kilometer-scale links.

In previous work, we reported data-in-flight on a micro-UAV (unmanned aerial vehicle) of 400 kbps and 910 kbps at ranges on the order of 35 meters.[4] In this effort, psuedo random codes varying from 300 kbps through 5 Mbps drove an array of five devices. Data was obtained with nominal bit error rates over ranges of 30 meters to 100 meters in daylight.

After the field test, real-time color video was transmitted over a 30-meter link in the laboratory using wavelet compression and a single cornercube retroreflector. Video was transmitted in an eyesafe regime at 1 Mbps at 15 frames per second and at up to 6 Mbps at 30 fps at higher incident power levels, though still eye-safe in light levels.

2.0 Multiple Quantum Well Modulating Retroreflectors

Modulating retroreflector (MRR) devices utilizing multiple quantum well (MQW) technology have a number of advantages. In addition to drawing milliwatts to support megabits per second, low mass, and compactness, they are inherently faster than alternatives. MQW retromodulators can support up to 12 Mbps with centimeter-level diameters and higher with millimeter-level diameters. [5] The devices are essentially narrow-band tunable optical filters and so they enable secure data transfer over carrier frequencies not susceptible to the band allocation problems characteristic of radio frequency links.

The devices are essentially PIN devices made from InGaAs/AlGaAs using molecular beam epitaxy (MBE). When a moderate voltage (in the range of 12V-20V) is placed across the device in reverse bias, the absorption feature changes, both shifting in wavelength and changing

in magnitude. Thus, the transmission of the device near this absorption feature changes dramatically and can serve as a solid-state on-off shutter. A schematic of the modulator architecture and switching capability is shown in Figures 1 and 2 for an InGaAs-based MQW modulator.

As shown in Figure 2, the device demonstrates how the contrast ratio changes as a function of drive voltage for the 980 nm device used in these experiments and how the device can be used as a tunable filter over a narrow range of wavelengths.

3.0 Field Test

Field tests were conducted at the NRL Chesapeake Bay Detachment facility in Chesapeake Beach, MD. A micro-UAV, a helicopter approximately 1.5 meters in length, was fitted with a payload consisting of an array of retromodulators, a digitizing unit, impedance matching driver circuitry, and requisite battery power packs.

3.1 Payload Configuration

Five 0.63-cm diameter InGaAs/AlGaAs modulators were used in this series of tests. The modulators were designed for surface normal transmissive operation. All were fabricated from the same wafer with a center frequency of 980 nm and bandwidth of approximately 10 nm. None were segmented. They were mounted in front of corner cube retroreflectors, which were anti-reflection coated at 980nm and had a protected silver coating on the reflecting surfaces.

The mounted devices each presented a 30-degree FWHM field-of-view and measured two centimeters in diameter. These devices were selected to perform within 5% of each other in terms of reflectance, contrast ratio, and switching speeds. The five units were situated in an elliptical array to compensate for reduced control of the model helicopter's motion in yaw. The

array was configured to present a 60-degree field-of-view to the interrogating laser. Each mounted retromodulator weighed 0.4 oz and the configured array on an aluminum mount weighed about 14 oz. A photo of the array is shown in Figure 3.

The modulators were driven in parallel with 12V to 15 V to provide contrast ratios of about 2:1 on all five units. A sequence of psuedo random codes were set in 2 second patterns of increasing bit rates from 300 kbps to 5 Mbps.

The array required less than 400 mW, or ~75 mW per retromodulator, and the microprocessor required 10 to 20 watts, depending on the data rate. No effort in this demonstration was made to minimize the power draw for the microprocessor.

3.2 Transmit/Receive

The helicopter was illuminated with an optical Transmit/Receive (Tx/Rx) design that employed an annular mirror for shared aperture transmit and receive. A 980 nm laser diode was fiber coupled to zoom optics which enabled changes in outgoing beam divergence from 2 mRad through 13 mRad. Received retroreflected light was directed to the tracking and detection optics and electronics by the mirror. A narrow band dichroic mirror split 90% of the 980 nm line to an avalanche photodiode. The remaining white light and 10% of the 980nm lights was directed to a small video camera which was used for in-line target acquisition and tracking. A block diagram of the system is shown in Figure 4.

A scintillometer recorded the structure constant, C_n^2, over the horizontal path simultaneously with the data acquired in flight. A portable weather station recorded relative humidity, barometric pressure, and temperature over the data taking periods as well.

3.3 Acquisition and Tracking

The pointing, acquisition, and tracking were accomplished with the in-line video signal, a DBA tracking unit, and an intensity-centering algorithm. The 10% pass-through of 980 nm light enabled self-tracking off of the array. This method is an improvement over the first demonstration in that LED's were not used to aid in acquisition and tracking. However, it was found that the in-line video tracking off of the helicopter was easier in full daylight, even with a narrow band filter in front of the acquisition camera.

Using the techniques described, the beam was kept on target continuously and ranges varied from about 30 meters to 100 meters for the tests. Elevation angles were about 30 to 45 degrees. This method is ultimately more efficient compared to an array of LEDs with a central MRR in terms of payload power requirements and offers a larger field-of-view for interrogation.

3.4 Results

Results for different data rates are shown in Figure 5. From this figure, it can be seen that the pulse trains are well discernible up to 5 Mbps. An electronic filter was put on the input of the digital recorder to filter out additional noise from the band but it is expected that the array could support greater than 5 Mbps with some degradation in bit error rate. Ranges for this data was on the order of 30 m to 100 m. It is expected that the devices, which were shown to support up to 10 Mbps in the laboratory, could support greater bandwidth for the field tests, if required.

The contrast ratio of the retromodulators was on the order of 2:1 when driven at 12V. The returns remained robust over the ranges and propagation occurred under relatively strong turbulence conditions in mid-day. We did not explore the complete parameter set in this demonstration but operated in the regime to support essentially nominal bit error rates (BER's)

over the link. The noise on the signal was due primarily to atmospheric effects, which was very evident at the longer ranges.

Figures 6 shows the power spectrum of modulated and unmodulated light captured in flight. A 30 mW output into a 12.5-milliradian beam presented an average incident flux on target of about 7 nJ/cm^2 at 30 meters and about 150 pJ/cm^2 at the longer ranges. Although the impact of the strong range dependence on the signal strength was evident in a reduction of average signal-to-noise at the longer ranges, the effect of atmosphere was clearly more pronounced, evidenced by larger noise fluctuations.

The BER is nominally zero for this flux at these ranges for all data rates tested. The structure constant for the horizontal path varied but was on the order of C_n^2= 4E(-13) with a high variance for most of the data acquisition period. This structure constant profile is a signature of high turbulence where closed form solutions based on Kolmogorov theory breaks down. Traces of the structure constant as a function of time is shown in Figure 7.

4.0 Color Video

4.1 Experiment

In this experiment, a Sony Camcorder was connected to an L3 wavelet compression unit using a standard NTSC interface. The output was then sent through an impedance matching circuit to drive one of the 980 nm retromodulators. This "payload" was then placed approximately 30 meters from the laser transmitter/receiver interrogator in a laboratory environment. The incident light from the 980nm source was varied from 5 mJ per cm^2 to 8 mJ per cm^2, where transfer at completely eyesafe light levels defined the bound. Frame and bit rates were varied to explore image quality. The L3 wavelet compression unit enables error corrective coding. We chose the Reed-Solomon block encoding option for transmission.

A photograph of the communications terminal is shown in Figure 8. The form factor for the compression unit is small - on the order of 8x3x10 cm. The mounted retromodulator measures about 2.5 cm on a side for a single unit. The modulator itself required 80 to 130 mW to drive the link. The compression unit required 9W, which dominated the power draw requirement.

4.2 Results

At the lower flux levels, a 1 Mbps link was supported and color video was transferred at 15 frames per second. At the higher flux levels, 30 fps were supported at 4 Mbps to 6 Mbps without significant bit drop-out[3]. Figure 9 shows still images of the transmission at 4 mbps at 30 fps inside the lab environment.

Based on qualitative analysis from the transmission, images at 15 fps are certainly informative enough to enable the observer to obtain useful information. When the beam was blocked, transmission stopped, freezing the frame. Frame recovery was on the order of milliseconds.

A key aspect in this demonstration was that the very low power required by the retromodulator unit itself exposed the power requirement of the digitizing component in the communications terminal. This points to a new area for technology investment for long-range sponsors.

5.0 New Initiatives

5.2 Eyesafe Retromodulators

In addition to the MQW devices designed and fabricated from 850 nm through 1.06 microns, we have begun to design and fabricate devices at 1550 nm. This wavelength is in the

[3] A real-time video link can be seen through our Web page at http://mrr.nrl.navy.mil/demonstrations.html.

“eyesafe” regime where substantial investment by the telecommunications industry has advanced the development of supporting components. In addition there is a significant transmission window through the earth’s atmosphere at this wavelength (4).

Lattice strain makes fabrication of effective devices using InGaAs/AlGaAs substrates and molecular beam epitaxy very difficult. The new devices are being designed in InGaAs/InAlAs . The new class of material relieves strain but presents a new set of challenges. The greater propensity to form defects from the manufacturing process can ultimately lead to limits in contrast ratios.

First MQW retromodulators were fabricated with one-millimeter diameters. When scaled to the 0.63 cm device, we can expect comparable performance to the 980 nm device in terms of modulation rates. Figures 10 and 11 show some performance results of these first devices. In Figure 10, absorbance plots indicate that contrast ratios of 2.3:1 are possible. Figure 11 shows that modulation rates of at least 20 Mbps are viable. Data rates of 40 Mbps were also supported by not shown. We will phase these into the field tests as the processing and fabrication matures.

5.3 “Cat’s Eye” Retromodulators

The MQW modulator is essentially a PIN device. As such, there is a fundamental trade between speed and power consumption, since both are limited by the Resistor-Capacitor time constant. That is, the speed is proportional to $1/R_{mod}D_{mod}^2$, where R_{mod} is the sheet resistance of the modulator and D_{mod} is the diameter. The power consumed is proportional to $D_{mod}^2V^2f$, where V is the drive voltage and voltage and f is the modulation rate.

The electrical characteristic of the MQW device limit the modulation rate to about 1-20 MHz/cm^2 and heating becomes a concern at the higher modulation rates due to the higher drive

power requirements. Consequently, there is a fundamental limit to the speed of the corner cube device. This has motivated the NRL to consider a new class of retromodulators: the "Cats Eye" retromodulator. [5,6]

In these devices, the "Cats Eye" retro architecture enables us to use a much smaller MQW modulator. Essentially, an array of very small devices - on the order of a millimeter each - can be placed in the pupil or focal plane of a cat's eye retromodulator, illuminating just one or a few "pixels" of the modulator array.. The MQW device is manufactured to exploit its ability to serve as a detector as well as a modulator. Only the ‘pixel’ or 'pixels' illuminated need be modulated. This approach enables much higher speeds and significantly lower drive powers. The trade is that the optics and supporting electronics are more complex and heavier. However the element still can be compact and lightweight compared to conventional laser communications terminals.

First devices were constructed using one millimeter 980 nm devices and a design using off-the-shelf optical components produced a 4 times-diffraction limited device. The devices supported a data rate of 40 Mbps. Figure 12 and 13 are a schematic of the idea and a photograph of the first reduction to practice, respectively.

Future work will include the design, fabrication, and testing of a diffraction-limited "Cats Eye. We will then combine it with 1550 nm devices as discussed in the previous section to create fast, eyesafe units which promise to provide more than a magnitude improvement in modulation rate.

6.0 Conclusions

This work reports progress in the use of the NRL Multiple Quantum Well retromodulators. Data-in-flight was recovered with essentially no bit errors for up to 5 Mbps in

the field using a five-element array of devices. Bandwidth was limited by an electronic filter used to filter out noise, not by the device itself. Ranges were on the order of 30m to 100m. Wavelet-compressed color video was transmitted using the device from 15 fps at 1 Mbps through 30 fps at 6 Mbps over 30 meters in the laboratory.

In future efforts we will mount the camera, compression unit, and impedance circuits with the array onto a micro UAV to obtain real-time video-in-flight. The work indicates that pointing can hold the beam on the array for requisited well times and the compressed video can be transferred effectively as shown in the lab. We will also explore parameter space for viable video links over longer ranges and lower intensities.

Device development at 1550 nm will continue as will the investigation of effective architectures to increase device speeds to better than 100 Mbps.

Acknowledgements

The Office of Naval Research and DARPA sponsored this work.

LIST OF FIGURES

FIGURE 7. Traces of the structure constant, C_n^2, as a function of time during the data-in-flight measurements. Instantaneous values varied significantly but the average value was on the order of 4E(-14).

FIGURE 8. A photograph of the communications terminal is shown. The unit was comprised of a 980 nm retromodulator coupled to an L3 wavelet compression unit, impedance-matching drive circuitry and power supply. The link was obtained with 130 mW on the modulator supporting up to 6 Mbps, 30 fps.

FIGURE 9. A still image of video transmission at 4 mbps at 30 fps inside the lab environment.

FIGURE 10. Absorbance vs. wavelength for 1550 nm devices. First efforts are yielding MQW modulators that have 2.3:1 contrast ratios.

FIGURE 11. Modulation traces are shown for the 1550 MQW devices. The one millimeter diameter devices are shown to support at least 20 Mbps.

FIGURE 12. The concept of a focal plane “Cat’s Eye” retromodulator is shown.

FIGURE 13. A photo of a first “Cat’s Eye” retromodulator is shown. This device supports on the order of 40 Mbps and is about 10 times the diffraction limit.

References

1. Gilbreath, G. C., et.al., "Modulating Retroreflector Using Multiple Quantum Well Technology", **U. S. Patent No. 6,154,299**, awarded November, 2000.
2. Katzer, D. S., et.al., “Optimization of Buffer Layers for InGaAs/AlGaAs PIN Optical Modulators Grown on GaAs Substrates by Molecular Beam Epitaxy,” *Jnl. of Vac. Sci. Tech.*, **B 18**, pp. 1609-1613, 2000.
3. Goetz, P. G., et al., "Effects of Proton Irradiation on InGaAs/AlGaAs Multiple Quantum Well Modulators", *Proc. of the IEEE Aerospace Conferenc*e, **5.0402**, March, 2001.
4. G. C. Gilbreath, et.al., "Large Aperture Multiple Quantum Well Modulating Retroreflector for Free Space Optical Data Transfer on Unmanned Aerial Vehicles", *Opt.Eng.*, **40** (7), pp. 1348-1356 (2001).
5. William S. Rabinovich, et. al., “A Cats Eye Multiple Quantum Well Modulating Retroreflector”, *Photonics Technology Letters*, submitted for peer review, January, 2002.
6. Mark. L. Bierman, et. al., "Design and analysis of a diffraction limited cat's eye retroreflector", *Opt. Eng*., **41**(7), pp. 1655-1660 (2002).

Figure 1

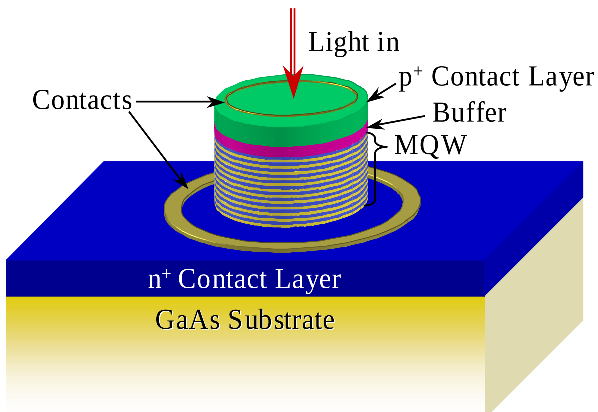

Light in
p+ Contact Layer
Contacts
Buffer
MQW
n+ Contact Layer
GaAs Substrate

Figure 2

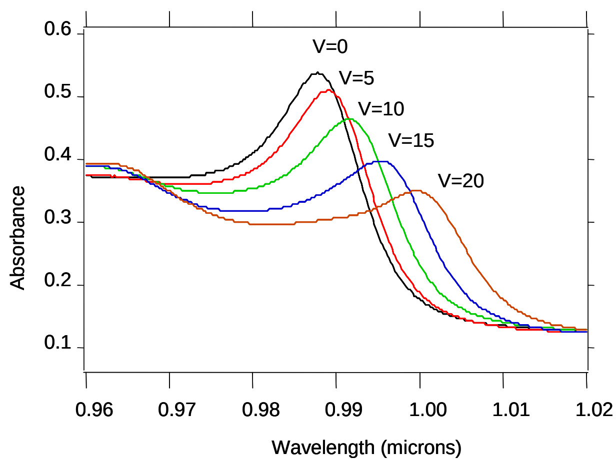

V=0
V=5
V=10
V=15
V=20
0.6
0.5
0.4
0.3
0.2
0.1
Absorbance
0.96
0.97
0.98
0.99
1.00
1.01
1.02
Wavelength (microns)

Figure 3

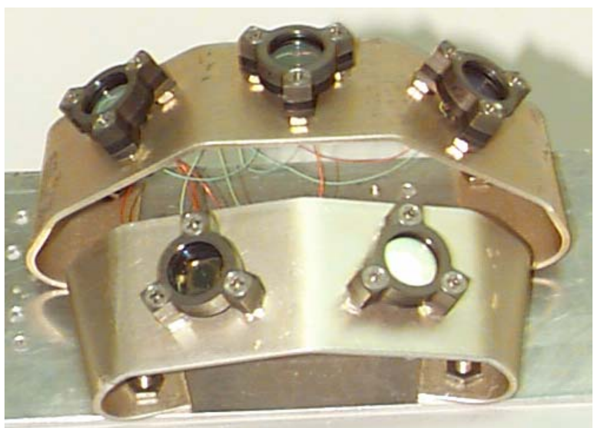


Figure 4

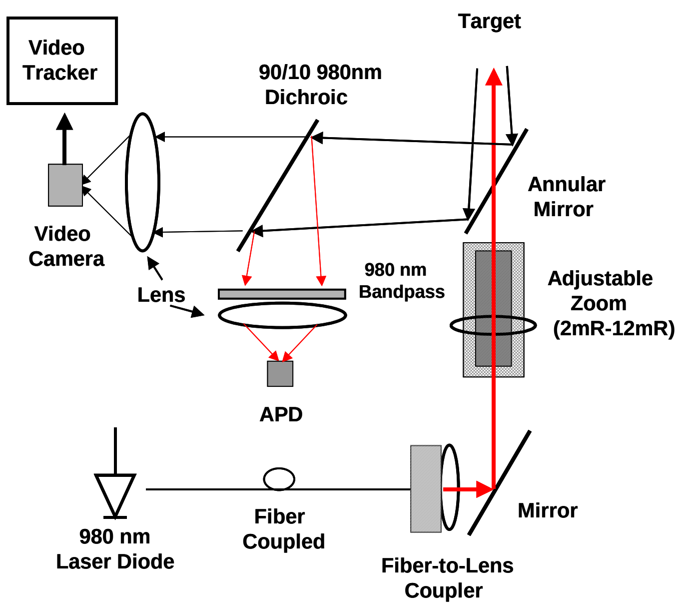
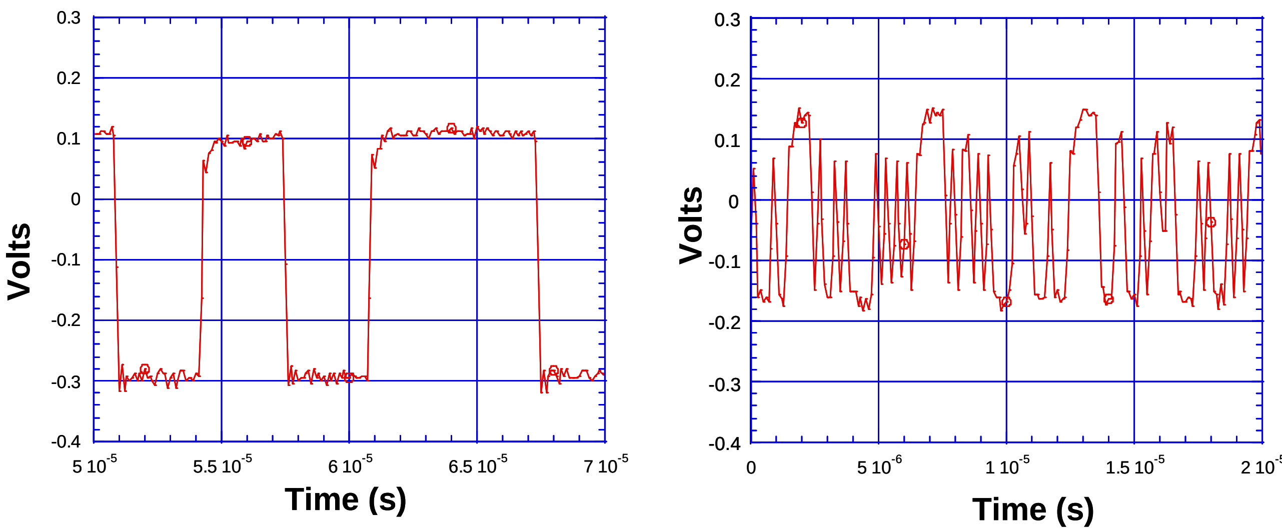

Video
Tracker
Target
90/10 980nm
Dichroic
Annular
Mirror
Video
Camera
980 nm
Bandpass
Adjustable
Zoom
(2mR-12mR)
Lens
APD
980 nm
Laser Diode
Fiber
Coupled
Mirror
Fiber-to-Lens
Coupler

Figure 5



Volts
Time (s)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
5 10-5
5.5 10-5
6 10-5
6.5 10-5
7 10-5
0
5 10-6
1 10-5
1.5 10-5
2 10-5

(a) **(b)**

Figure 6

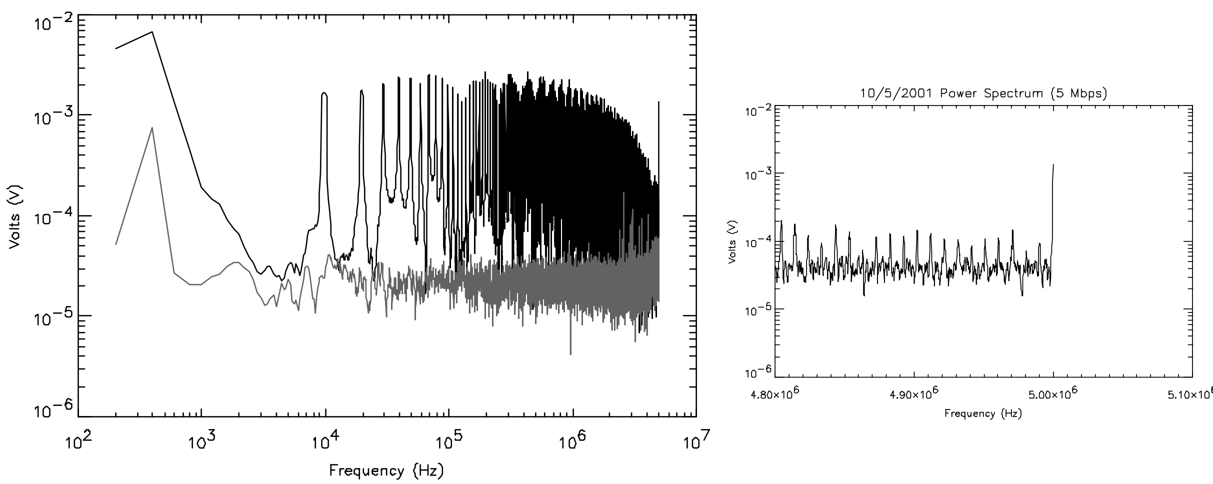
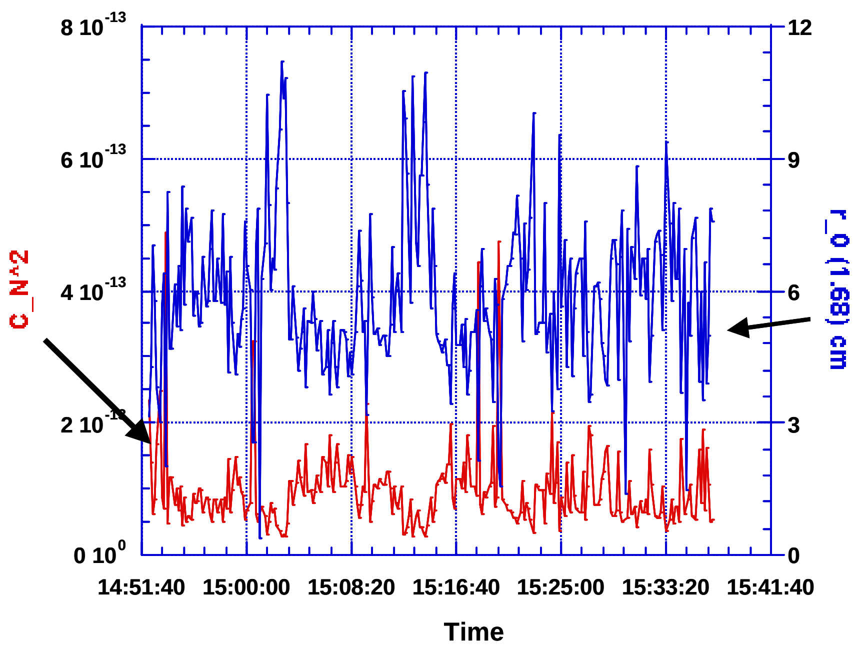


Figure 7



8 10-13
6 10-13
4 10-13
2 10-13
0 10^0
C_N^2
12
9
6
3
0
r_0 (1.68) cm
14:51:40
15:00:00
15:08:20
15:16:40
15:25:00
15:33:20
15:41:40
Time

Figure 8

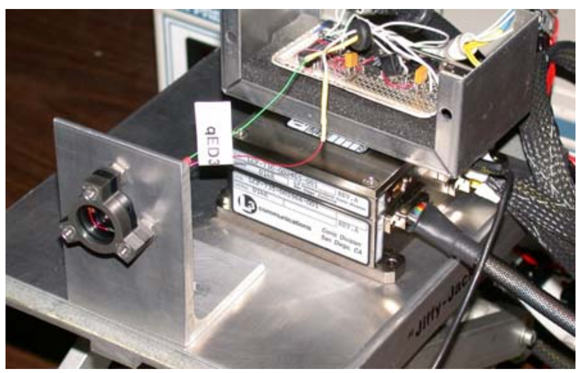
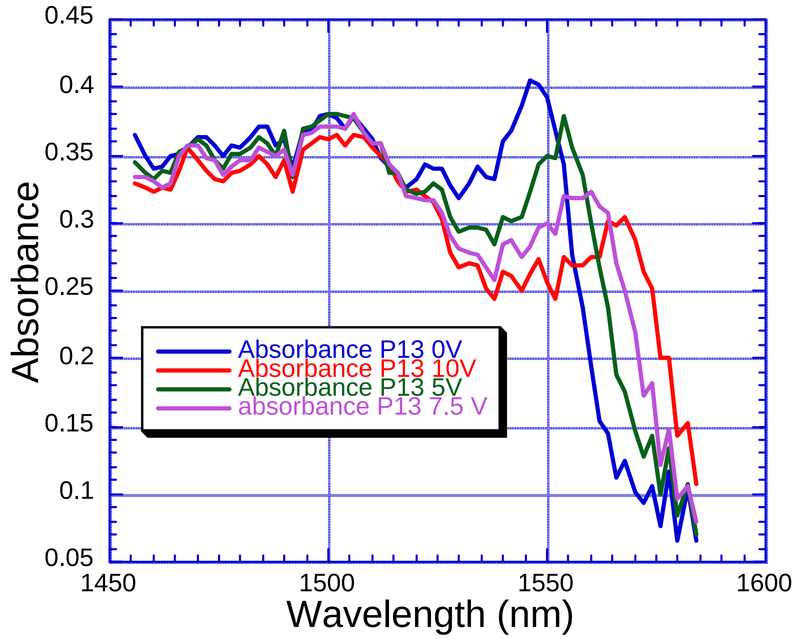


Figure 9

Figure 10



Absorbance
Wavelength (nm)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
1450
1500
1550
1600
Absorbance P13 0V
Absorbance P13 10V
Absorbance P13 5V
absorbance P13 7.5 V

Figure 11

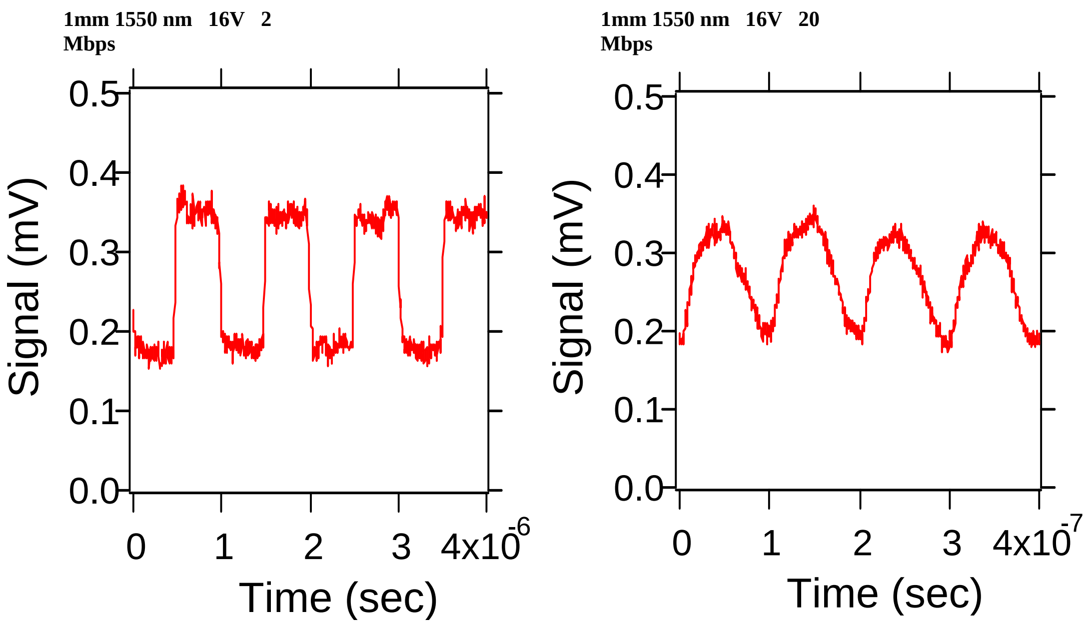

1mm 1550 nm 16V 2
Mbps
Signal (mV)
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4x10-6
Time (sec)
1mm 1550 nm 16V 20
Mbps
Signal (mV)
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4x10-7
Time (sec)

Figure 12

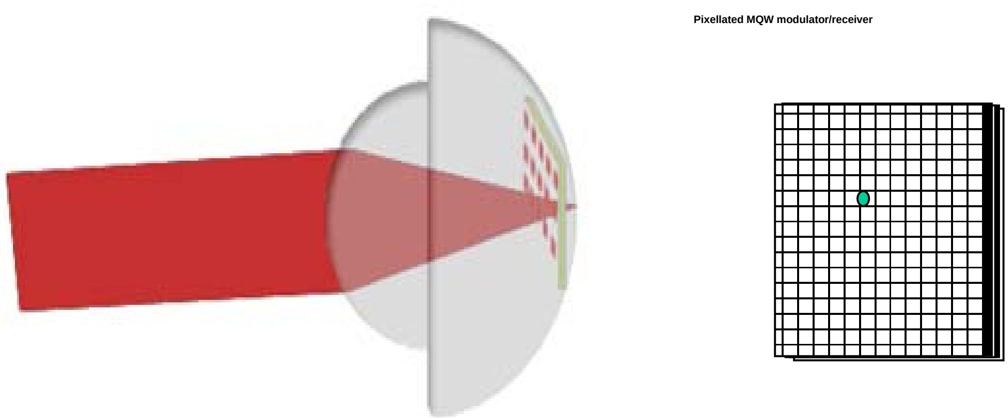


Figure 13